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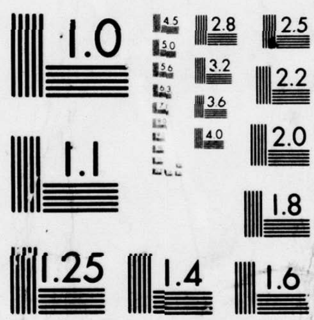

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Final Technical Report
January 1977

PROPAGATION AND RECEPTION OF PARTIALLY COHERENT WAVES IN RANDOM MEDIA

University of Washington

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ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

Prof. Akira Ishimaru is the Principal Investigator for this contract. Koichi Mano is the RADC Project Engineer (Contract Monitor).

This report has been reviewed by the RADC Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

This technical report has been reviewed and approved for publication.

APPROVED:

KOICHI MANO

APPROVED:

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Acting Chief
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The final report gives a summary of all the work completed and underway under this contract covering the period from July 1973 to September 1976. ~~The~~ This work covers a broad spectrum including wide-band pulse propagation in a time-varying medium, turbulence, fog, rain, cloud and other discrete scatterers, relationship between transport theory and multiple scattering theory, back-scattering of pulses, remote-sensing, intensity fluctuations, coherence → next page
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(from block 20: abstract)

bandwidth, coherence time, and pulse shape distortion of millimeter waves in rain, fog, and turbulence, radiometric measurement of rain attenuation.

Our emphasis is directed towards generating new ideas and techniques to solve important practical problems. Success in our effort is evidenced by the list of reports and publications in this final report.

EVALUATION

1. This is the Final Report on the contract which over the period from 1 July 73 to 30 September 76 investigated analytically the wave propagation phenomenon in turbulence and in random distribution of discrete scatterers. Propagation of plane, spherical, and beam waves, and of pulse and wideband waves were studied with a view toward generating new techniques for solving problems in this area.

2. The above work is of value since it determines the effects of atmospheric turbulence and discrete scatterers, such as rain, fog, and snow, on propagation of millimeter and optical waves. The basic knowledge on these effects thus obtained will be used by the Air Force for design of the communication and radar systems.

Koichi Mano

KOICHI MANO
Project Engineer
Tropospheric Propagation Branch
Electromagnetic Sciences Division

TABLE OF CONTENTS

I. Introduction

Our effort for the past three years has been centered on the following subjects: (1) Wide-band pulse propagation in turbulence, (2) Wide-band pulse propagation in rain, fog, and cloud, (3) backscattering from a dense medium and (4) radiometric determination of rain attenuation at millimeter wavelength.

Our primary effort has been concentrated on generating new ideas and techniques to solve important practical problems for which no solutions are available at present.

A brief description of our research in each area is given in this report and a list of reports and publications of our laboratory is included.

II. Wide-Band Pulse Propagation in Turbulence

The general formulation of the propagation characteristics of a short pulse in turbulence has been obtained in terms of the spectral representation of the pulse and the two-frequency mutual coherence function. This formulation is applicable to time-varying as well as time-invariant turbulence.

For the case where turbulent eddy sizes are much greater than a wavelength, two-frequency mutual coherence function is shown to satisfy a parabolic differential equation. This is an extension of the usual parabolic equation for the single-frequency case. In general, this equation can not be solved analytically, and approximate solutions must be obtained in different ranges.

When the optical distance is less than 3, we can obtain a convenient analytical solution. This has been discussed in Scientific Report No. 4. In this range, the mutual coherence function consists of the coherent and the incoherent parts. The coherent part is substantially independent of difference frequency and the coherent pulse has a shape similar to the input pulse with attenuation equal to the optical distance. The incoherent part diminishes to zero with the increase of the difference frequency, and the incoherent pulse spreads out in time.

In the range where the optical distance is between 3 and 25, no analytical solution is available. We used numerical techniques to calculate the mutual coherence function and the pulse shape. The coherent pulse almost disappears and the incoherent pulse becomes dominant. In the range where the optical distance is greater than 25, the coherent part is almost totally gone and the parabolic equation is considerably simplified. We can then normalize the differential equation and obtain a numerical solution applicable to a wide variety of situations. The mutual coherence function and the pulse shape in this range have universal forms.

This universal solution is studied in detail for neutral atmosphere and ionized turbulence. The result for ionized turbulence is compared with pulses from pulsars. The pulse broadening as a function of the carrier (observation) wavelength shows a reasonable aggreement between theory and measurement.

If the spectrum of the random medium is gaussian rather than the Kolmogorov, then the differential equation can be solved exactly and an analytical solution can be obtained both for mutual coherence function and pulse shape. This is a universal form and is convenient to establish relationships among various parameters such as distance, wavelength, the strength of the random medium, and pulse shape.

Two-frequency mutual coherence function is a function of two different frequencies ω_1 and ω_2 and two different times t_1 and t_2. If we express this as a function of the center frequency ω_c and the difference frequency ω_d and the center time t_c and the time difference t_d, then for a given ω_c and t_c, the two-frequency mutual coherence function describes the correlation characteristics in frequency ω_d and time t_d. The dependence on frequency ω_d is characterized by the coherence bandwidth and the dependence on time t_d is characterized by the coherence time. The inverse of the coherence bandwidth represents pulse broadening and the inverse of the coherence time represents broadening of the temporal frequency spectrum.

With the above studies, the propagation characteristics of a pulse in a turbulence have been well clarified for the second moment and the average intensity. The intensity fluctuation of a pulse has not been studied yet.

III. Wide-Band Pulse Propagation in Rain, Fog and Cloud

Pulse propagation in a random distribution of scatterers such as rain drops, fog and cloud droplets can be investigated following the general formulations for a pulse propagation in turbulence. For scatterers, however, the scattering amplitude of a single particle plays a role similar to the spectral density of turbulence. Integral and differential equations for two-frequency mutual coherence function are obtained from multiple scattering theory. These equations are consistent with the equation of transfer and in the limit of a single frequency, they reduce to the equation of transfer. For particles with sizes greater than a wavelength, the differential equation can be simplified and a parabolic equation similar to that for turbulence can be obtained. In fact, mathematically for both turbulence and scatterers, the differential equations for two-frequency mutual coherence function have the same general form, and therefore the techniques employed to solve the turbulence problem can be used to solve the pulse propagation in scatterers.

Detailed study has been made of pulse propagation in fog and rain. The coherence time and the coherence bandwidth have been calculated for millimeter and optical waves. It has been determined that the effect of rain on coherence bandwidth is small at optical frequency but is considerable at millimeter frequencies. Fog and cloud severely limit the coherence bandwidth of an optical beam.

IV. Backscattering from a Dense Medium

Single scattering solutions of cw and pulse waves are simple and well known. However multiple scattering solution is still not satisfactory. Some available solutions based on a diagram method show that the cw solution approaches twice the single scattering solution and is different from the radiative transfer solution. Since the wave enters into the medium, interacts with the medium and returns from the medium, the mutual coherence function of the backscattered wave is proportional to the fourth order moment and therefore no exact solution is available at present. We have attempted to obtain a backscattered pulse solution. However further study is required to obtain a useful solution.

V. Radiometric Determination of Rain Attenuation at Millimeter Wavelength

The determination of rain attenuation by radiometric technique is normally made with an assumption that particle scattering is negligible. This is true only for frequencies below 30 GHz. We have initiated a study to include the effects of multiple scattering applicable to all millimeter wavelengths.

A complete study of this problem requires solution of equation of transfer by eigenvalue technique or invariant-imbedding technique. We also explored possibility of obtaining useful approximate solutions. They include isotropic scattering, diffusion approximation, and forward scattering approximations. We expect to obtain some useful solutions shortly.

VI. Personnel

Dr. Akira Ishimaru, Principal Investigator.

Research Assistant	Degree Granted
Mr. S. T. Hong	March 1975 Ph.D.
Mr. I. Sreenivasiah	December 1976 Ph.D

VII Journal Publications Related to this Contract F19628-74-C-0005 (1 July 1973 to present)

(1) J. Michael Heneghan and A. Ishimaru, "Remote Determination of the Profiles of the Atmospheric Structure Constant and Wind Velocity Along a Line-of-Sight Path by a Statistical Inversion Procedure," IEEE Trans on Antennas and Propagation, Vol AP-22, No. 3, 457-464, 1974.

(2) R. Woo, A. Ishimaru, and W. B. Kendall, "Observations of Small-Scale Turbulence in the Atmosphere of Venus by Mariner 5. "J. of Atmospheric Sciences, Vol 31, No. 6, pp. 1698-1706, September 1974.

(3) J. C. Lin and A. Ishimaru, "Multiple Scattering of Waves by a Uniform Random Distribution of Discrete Isotropic Scatterers, "J. of Acoustic Society of America, Vol 56, 6, 1695-1700, December 1974.

(4) A. Ishimaru, "Correlation Functions of a Wave in a Random Distribution of Stationary and Moving Scatterers," Radio Science, special issue, Vol 10, No. 1, 45-52, January 1975.

(5) A. Ishimaru, "The Beam Wave Case and Remote Sensing," a chapter in a book, "Laser Beam Propagation through the Atmosphere," Topics in Applied Physics, Springer-Verlag, 1975.

(6) A. Ishimaru and S. T. Hong, "Multiple Scattering Effects on Coherent Bandwidth and Pulse Distortion of a Wave propagating in a Random Distribution of Particles," Radio Science, Vol 10, 6, pp. 637-644. June 1975.

(7) S. T. Hong and A. Ishimaru, "Two-frequency Mutual Coherence Function, Coherence Bandwidth and Coherence Time of Millimeter and Optical Waves in Rain, Fog, and Turbulence," Radio Science, Vol 11, 6, pp. 551-559, June 1976.

(8) I. Sreenivasiah, A. Ishimaru, and S. T. Hong, "Two-frequency Mutual Coherence Function and Pulse Propagation in a Random Medium: An Analytic Solution to Plane Wave Case," Radio Science, to be published.

(9) S. T. Hong, I. Sreenivasiah, and A. Ishimaru, "Pulse Propagation through a Random Medium," submitted to IEEE Trans. Antennas and Propagation.

VIII. Scientific Reports under F19628-C-0005 (1 July 1973 to present)

(1) A. Ishimaru and S. T. Hong, "Propagation Characteristics of a Pulse Wave in a Discrete Time-Varying Random Medium" Scientific Report No. 1, March 1974, (AFCRL-TR-0196).

(2) A. Ishimaru and I. Sreenivasiah, "Plane Wave Pulse Propagation through Atmospheric Turbulence at mm and Optical Wavelengths," Scientific Report No. 2, March 1974 (AFCRL-TR-0205).

(3) A. Ishimaru, "Correlation Functions of a Wave in a Random Distribution of Stationary and Moving Scatterers," Scientific Report No. 3 (Reprint from Radio Science).

(4) A. Ishimaru and S. T. Hong, "Multiple Scattering Effects on Coherent Bandwidth and Pulse Distortion of a Wave Propagating in a Random Distribution of Particles," Scientific Report No. 4 (Reprint from Radio Science).

(5) S. T. Hong and A. Ishimaru, "Two-Frequency Mutual Coherence Function, Coherence Bandwidth and Coherent Time of Millimeter and Optical Waves in Rain, Fog, and Turbulence," Scientific Report No. 5, to be submitted for review when reprints become available.

(6) I. Sreenivasiah, A. Ishimaru, and S. T. Hong, "Two-Frequency Mutual Coherence Function and Pulse Propagation in a Random Medium: An Analytical Solution to Plane Wave Case," Scientific Report No. 6 to be submitted for review when reprints become available.

(7) S. T. Hong, I. Sreenivasiah and A. Ishimaru, "Pulse Propagation through a Random Medium," Scientific Report No. 7.

(8) A. Ishimaru, "The Beam Wave Case and Remote Sensing," Scientific Report No. 8 (Reprint from Topics in Applied Physics) to be submitted for review when reprints become available.

(9) A. Ishimaru and I. Sreenivasiah, "Backscattering of a Pulse from Turbulence," Scientific Report No. 9, in preparation.

IX. Paper Presentation and Meeting Attendance (1 July 1973 to present)

(1) A. Ishimaru, "Wide-Band Wave Propagation in Time-Varying Turbulence and Moving Discrete Scatterers, "URSI meeting, Boulder, August 1973.

(2) A. Ishimaru, "Pulse Propagation in Time-Varying Media," the URSI Symposium on Electromagnetic Theory, London, July 1974.

(3) A. Ishimaru and S. T. Hong, "Millimeter and Optical Pulse Propagation through a Random Distribution of Particles," URSI meeting, Atlanta, June 1974.

(4) A. Ishimaru and I. Sreenivasiah, "Optical Pulse Propagation in Turbulence" OSA Topical meeting, Boulder, July 1974.

(5) A. Ishimaru and S. T. Hong, "Multiple Scattering Effects on Coherent Bandwidth and Pulse Distortion in Discrete Scatterers," URSI meeting, Illinois, June 1975.

(6) S. T. Hong and A. Ishimaru, "Mutual Coherence Function, Coherence Bandwidth and Coherence Time of Millimeter and Optical Waves in Rain, Fog, and Turbulence," URSI meeting, Boulder, Colorado, October 1975.

(7) A. Ishimaru, "Some Recent Developments in Wave Propagation and Scattering in Random Media and their Applications," National Conference on Electromagnetic Scattering, June 15-18, 1976, University of Illinois at Chicago Circle.

(8) S. T. Hong, I. Sreenivasiah, and Akira Ishimaru, "Pulse Propagation in a Random Medium," URSI meeting, October 1976, Amherst, Mass.

(9) Akira Ishimaru, "Limitation on Image Resolution Imposed by a Random Medium," OSA meeting, October 1976, Tucson.

(10) Akira Ishimaru, "Atmospheric Effects on Pulse Propagation," NSF workshop on optical communication, November 1976, Seattle.

X. Other Activities Related to this Contract

(1) A. Ishimaru was a guest editor of a special issue of Radio Science on "Waves in Random Media," published in January 1975.

(2) A. Ishimaru chaired a special session on "Waves in Random Media" at the URSI meeting, October 1974.

(3) A. Ishimaru completed a chapter on "Beam Wave and Remote-Sensing" for the Springer-Verlag's topics in applied physics on "Laser Beam Propagation through the Atmosphere."

(4) A. Ishimaru completed an invited tutorial paper on "Waves in Random Media," for the Proceedings of IEEE, to be published July 1977.

(5) A. Ishimaru completed a manuscript for a book on "Wave Propagation and Scattering in Random Media," Academic Press.

(6) A. Ishimaru was appointed a Distinguished National Lecturer of IEEE AP-S for two years starting January 1976. The topic of the lecture is "Wave Propagation and Scattering in Random Media," This lecture was given at the University of Michigan, January 14 and at Ohio State University, January 15.

(7) A. Ishimaru was invited to chair a session and appointed a committee chairman to prepare a report at the National Conference on Electromagnetic Scattering, June 15-18, 1976

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